MODELING AND SIMULATION OF PV ARRAY WITH BOOST CONVERTER: AN OPEN LOOP STUDY

A THESIS IN PARTIAL FULFILMENTS OF REQUIREMENTS FOR THE AWARD OF THE DEGREE OF
Bachelor of Technology

Submitted to

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

BY

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NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

CERTIFICATE

This is to certify that the thesis entitled **“**Modeling and simulation of PV array with boost converter : An open loop study**”** submitted by Debashis Das (107EE024) and Shishir Kumar Pradhan (107EE039) in the partial fulfillment of the requirements for the award of Bachelor of Technology degree in Electrical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date:

Prof. Somnath Maity

Dept. of Electrical Engineering

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ABSTRACT

The recent upsurge in the demand of PV systems is due to the fact that they produce electric power without hampering the environment by directly converting the solar radiation into electric power. However the solar radiation never remains constant. It keeps on varying throughout the day. The need of the hour is to deliver a constant voltage to the grid irrespective of the variation in temperatures and solar insolation. We have designed a circuit such that it delivers constant and stepped up dc voltage to the load. We have studied the open loop characteristics of the PV array with variation in temperature and irradiation levels. Then we coupled the PV array with the boost converter in such a way that with variation in load, the varying input current and voltage to the converter follows the open circuit characteristic of the PV array closely. At various insolation levels, the load is varied and the corresponding variation in the input voltage and current to the boost converter is noted. It is noted that the changing input voltage and current follows the open circuit characteristics of the PV array closely.

Chapter **1**

INTRODUCTION

1.1 MOTIVATION

The Conventional sources of energy are rapidly depleting. Moreover the cost of energy is rising and therefore photovoltaic system is a promising alternative. They are abundant, pollution free, distributed throughout the earth and recyclable. The hindrance factor is it's high installation cost and low conversion efficiency. Therefore our aim is to increase the efficiency and power output of the system. It is also required that constant voltage be supplied to the load irrespective of the variation in solar irradiance and temperature. PV arrays consist of parallel and series combination of PV cells that are used to generate electrical power depending upon the atmospheric conditions (e.g solar irradiation and temperature). So it is necessary to couple the PV array with a boost converter. Moreover our system is designed in such a way that with variation in load, the change in input voltage and power fed into the converter follows the open circuit characteristics of the PV array. Our system can be used to supply constant stepped up voltage to dc loads.

1.2 WORK SUMMARY

We have discussed about the renewable energy, solar energy, distribution of solar radiation reaching the earth's surface and spectrum of sun in chapter 2. The details regarding the PV cell have been discussed in chapter 3. The PV array has been designed in MATLAB environment. The open-circuit characteristic of the PV cell has been studied in depth. The boost converter design, the coupling of the PV array with the converter has been described in chapter 4. The chapter 5 deals with the simulation results and discussions part. The P-V, I-V, P-I curves have been obtained at varying irradiation levels and temperatures. The generation of the PWM signal has been shown. We get constant voltage across the load resistance of the boost converter. Output load of the boost converter is varied and the variation in the input voltage and current fed into the boost converter is noted. The various values of the voltage and current have been plotted in the open loop curves of the PV array. The voltage and current values lie on the curves and thereby prove that our coupling of the boost converter with the PV array is proper.

Chapter **2**

PRELIMINARIES

2.1 RENEWABLE ENERGY

Renewable energy sources also called non-conventional type of energy are the sources which are continuously replenished by natural processes. Such as, solar energy, bio-energy - bio-fuels grown sustainably, wind energy and hydropower etc., are some of the examples of renewable energy sources. A renewable energy system convert the energy found in sunlight, falling-water, wind, sea-waves, geothermal heat, or biomass into a form, which we can use in the form of heat or electricity. The majority of the renewable energy comes either directly or indirectly from sun and wind and can never be fatigued, and therefore they are called renewable [12].

However, the majority of the world's energy sources came from conventional sources- fossil fuels such as coal, natural gases and oil. These fuels are often term non-renewable energy sources. Though, the available amount of these fuels are extremely large, but due to decrease in level of fossil fuel and oil level day by day after a few years it will end. Hence renewable energy source demand increases as it is environmental friendly and pollution free which reduces the greenhouse effect [12].

2.2 SOLAR ENERGY

Solar energy is a non-conventional type of energy. Solar energy has been harnessed by humans since ancient times using a variety of technologies. Solar radiation, along with secondary solar-powered resources such as wave and wind power, hydroelectricity and biomass, account for most of the available non-conventional type of energy on earth. Only a small fraction of the available solar energy is used [13].

Solar powered electrical generation relies on photovoltaic system and heat engines. Solar energy's uses are limited only by human creativity. To harvest the solar energy, the most common way is to use photo voltaic panels which will receive photon energy from sun and convert to electrical energy. Solar technologies are broadly classified as either passive solar or active solar depending on the way they detain, convert and distribute solar energy.

Active solar techniques include the use of PV panels and solar thermal collectors to strap up the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties and design spaces that naturally circulate air [5].Solar energy has a vast area of application such as electricity generation for distribution, heating water, lightening building, crop drying etc.

2.3 DISTRIBUTION OF SOLAR RADIATION

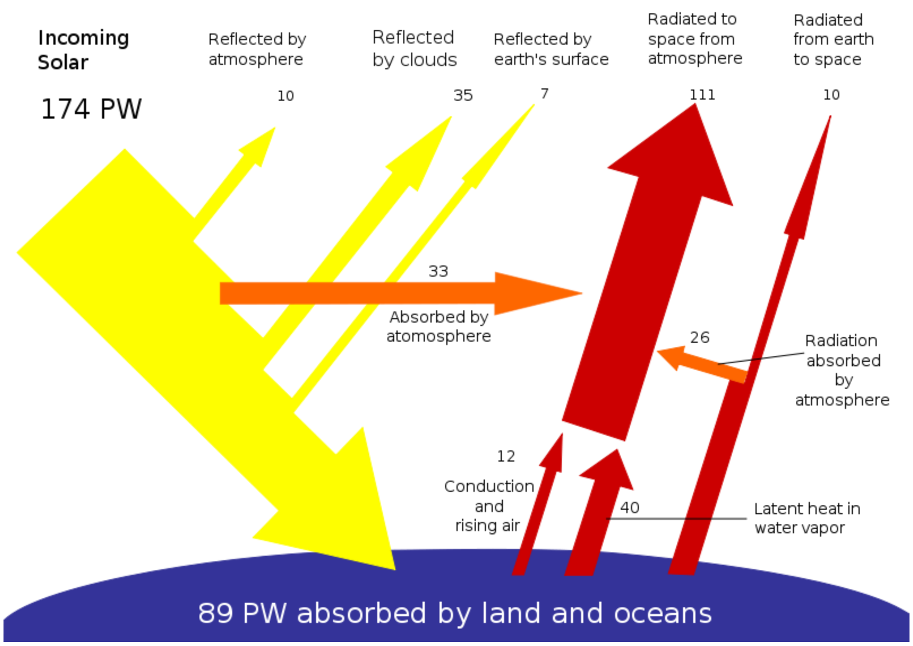

Figure 2.1 Solar radiation distribution [18].

From the above Figure 2.1 of solar radiation, Earth receives 174 petawatts (PW) of incoming solar radiation at the upper atmosphere. Approximately 30% is reflected back to space and only 89 pw is absorbed by oceans and land masses. The spectrum of solar light at the Earth's surface is generally spread across the visible and near-infrared reason with a small part in the near-ultraviolet. The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 EJ per year [13].

2.4 SOLAR RADIATION REACHING EARTH SURFACE

The intensity of solar radiation reaching earth surface which is 1369 watts per square meter is known as Solar Constant. It is important to realize that it is not the intensity per square meter of the Earth’s surface but per square meter on a sphere with the radius of 149,596,000 km and with the Sun at its centre.

The total amount solar radiation intercepted by the Earth is the Solar Constant multiplied by the cross section area of the Earth. If we now divide the calculated number by the surface area of the Earth, we shall find how much solar radiation is received in an average per square meter of the Earth's surface [10]. Hence the average solar radiation R per square meter of the Earth surface is,

$$\mathrm{R} = \frac{S \times \pi r^2}{4 \times \pi r^2} = \frac{1369}{4} = \text{approx.}\, 342\frac{w}{m^2}$$

where S is the solar constant ($1369\frac{W}{m^2}$), r is the earth radius.

The Handy formula which is used to calculate solar energy received by earth

$$\mathrm{E}=3.6*(10^{-9})*\mathrm{S}*\mathrm{n}*r^2$$

where *E* is the solar energy in EJ.

S is the Solar Constant in W/m^2.

n is the number of hours.

r is the Earth's radius in km [10].

2.5 SPECTRUM OF SUN

The performance of Photovoltaic device is reliant on the spectral distribution of solar radiation. The standard spectral distribution is mainly used as reference for evaluation of PV devices. There are two standard terrestrial distribution defined by the American Society for Testing and Materials (ASTM), global AM1.5 and direct normal. The solar radiation that is perpendicular to a plane directly facing the sun is known as direct normal. The global corresponds to the spectrum of the diffuse radiations. Diffuse radiations are the radiations which are reflected on earth's surface or influenced by atmospheric conditions. To measure the global radiations an instrument named pyranometer is used. This instrument is designed in such a way that it responds to each wavelengths and so that we get a precise value for total power in any incident spectrum [5].

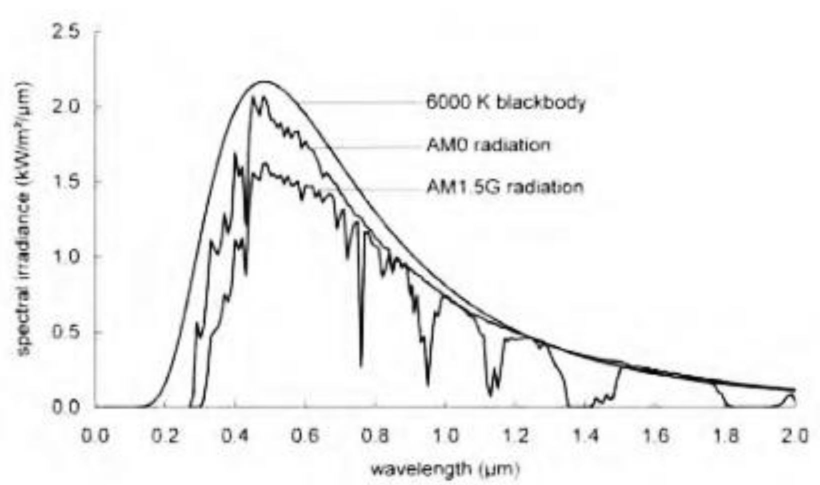

Figure 2.2 Spectral distribution of black body radiation and sun radiation [11].

The AM initials in the above Figure stands for air mass. The air mass in this circumstance means the mass of air between a surface and the sun [6]. The length of the path of solar radiation from the sun through the atmosphere is indicated by the number AMx. The longer the path the more is the deviation of light. The AM0 in the above figure means the spectral distribution and intensity of sunlight in near-earth space without atmospheric attenuation [6].

2.6 STANDARD TEST CONDITIONS (STC)

The comparison between different photovoltaic cells can be done on the basis of there performance and characteristic curve. The parameters are always given in datasheet. The datasheet make available the notable parameter regarding the characteristics and performance of PV cells with respect to standard test condition.

Standard test conditions are as follows:

Temperature (T_n) = 25^0c

Irradiance (G_n) = $1000\frac{W}{m^2}$

Spectrum of x = 1.5 i.e. AM.

Chapter **3**

PHOTOVOLTAIC SYSTEMS

3.1 DEFINITION

A photovoltaic system is a system which uses one or more solar panels to convert solar energy into electricity. It consists of multiple components, including the photovoltaic modules, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output [14].

3.2 PHOTOVOLTAIC ARRANGEMENTS

3.2.1 PHOTOVOLTAIC CELL

PV cells are made of semiconductor materials, such as silicon. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current - that is, electricity. This electricity can then be used to power a load[16]. A PV cell can either be circular or square in construction.

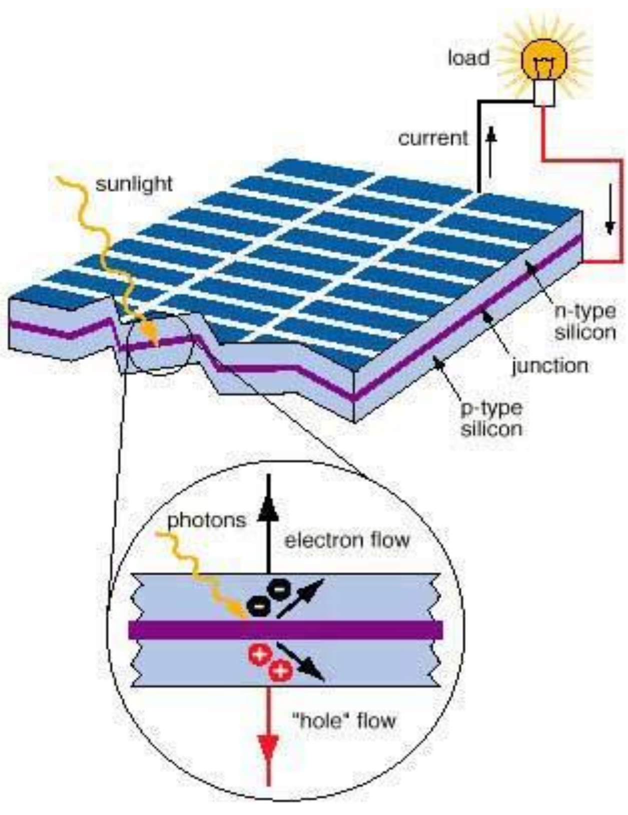

Figure 3.1 Basic Structure of PV Cell

3.2.2 PHOTOVOLTAIC MODULE

Due to the low voltage generated in a PV cell (around 0.5V), several PV cells are connected in series (for high voltage) and in parallel(for high current) to form a PV module for desired output. Separate diodes may be needed to avoid reverse currents, in case of partial or total shading, and at night. The p-n junctions of mono-crystalline silicon cells may have adequate reverse current characteristics and these are not necessary. Reverse currents waste power and can also lead to overheating of shaded cells. Solar cells become less efficient at higher temperatures and installers try to provide good ventilation behind solar panels [15].

3.2.3 PHOTOVOLTAIC ARRAY

The power that one module can produce is not sufficient to meet the requirements of home or business. Most PV arrays use an inverter to convert the DC power into alternating current that can power the motors, loads, lights etc. The modules in a PV array are usually first connected in series to obtain the desired voltages; the individual modules are then connected in parallel to allow the system to produce more current [14].

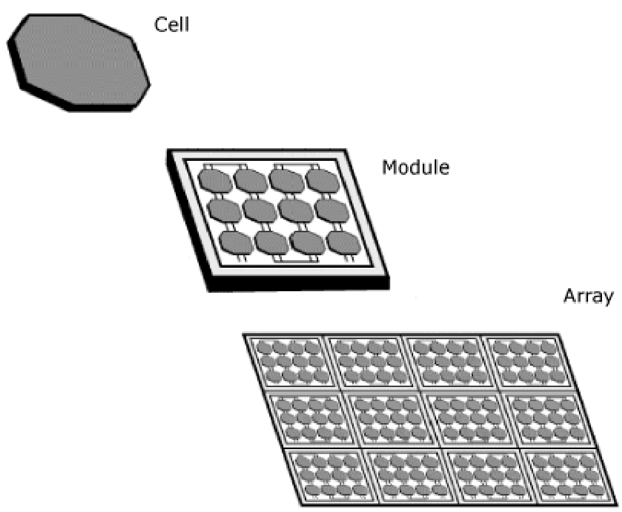

Figure 3.2 Photovoltaic system [16]

3.3 MATERIALS USED IN PV CELL

The materials used in PV cells are as follows:

- Single-crystal silicon

Single-crystal silicon cells are the most common in the PV industry. The main technique for producing single-crystal silicon is the Czochralski (CZ) method. High-purity polycrystalline is melted in a quartz crucible. A single-crystal silicon seed is dipped into this molten mass of polycrystalline. As the seed is pulled slowly from the melt, a single-crystal ingot is formed. The ingots are then sawed into thin wafers about 200-400 micrometers thick (1 micrometer = 1/1,000,000 meter). The thin wafers are then polished, doped, coated, interconnected and assembled into modules and arrays [7].

- Polycrystalline silicon

Consisting of small grains of single-crystal silicon, polycrystalline PV cells are less energy efficient than single-crystalline silicon PV cells. The grain boundaries in polycrystalline silicon hinder the flow of electrons and reduce the power output of the cell. A common approach to produce polycrystalline silicon PV cells is to slice thin wafers from blocks of cast polycrystalline silicon. Another more advanced approach is the “ribbon growth” method in which silicon is grown directly as thin ribbons or sheets with the approach thickness for making PV cells [7].

- Gallium Arsenide (GaAs)

A compound semiconductor made of two elements: Gallium (Ga) and Arsenic (As). GaAs has a crystal structure similar to that of silicon. An advantage of GaAs is that it has high level of light absorptivity. To absorb the same amount of sunlight, GaAs requires only a layer of few micrometers thick while crystalline silicon requires a wafer of about 200-300 micrometers thick. Also, GaAs has much higher energy conversion efficiency than crystal silicon, reaching about 25 to 30%.The only drawback of GaAs PV cells is the high cost of single crystal substrate that GaAs is grown on [7].

- Cadmium Telluride (CdTe)

It is a polycrystalline compound made of cadmium and telluride with a high light absorbility capacity (i.e a small thin layer of the compound can absorb 90% of solar irradiation).The main disadvantage of this compound is that the instability of PV cell or module performance. As it a toxic substance, the manufacturing process should be done by extra precaution [7].

- Copper Indium Diselenide ($CuInSe_2$)

It is a polycrystalline compound semiconductor made of copper, indium and selenium. It delivers high energy conversion efficiency without suffering from outdoor degradation problem. It is one of the most light-absorbent semiconductors. As it is a complex material and toxic in nature so the manufacturing process face some problem [7].

3.4 CHARACTERISTICS OF PV CELL

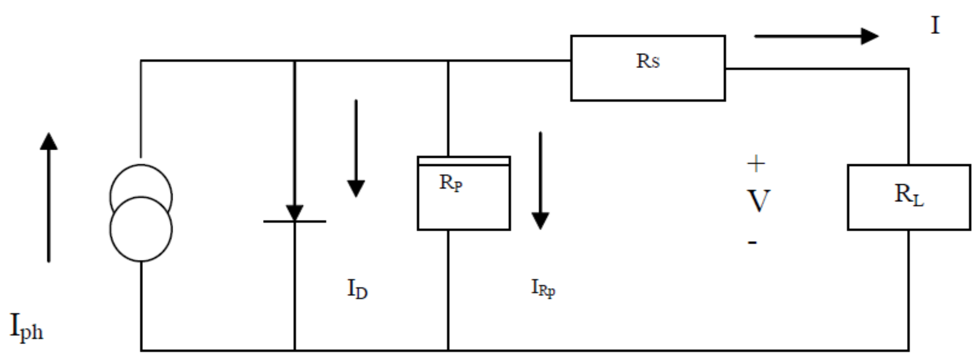

Figure 3.3 Equivalent circuit of a PV cell

An ideal is modeled by a current source in parallel with a diode. However no solar cell is ideal and thereby shunt and series resistances are added to the model as shown in the PV cell diagram above. R_S is the intrinsic series resistance whose value is very small. R_P is the equivalent shunt resistance which has a very high value [4].

Applying Kirchoff's law to the node where $I_{ph,}$ diode, R_p and R_s meet, we get

$$I_{ph}=I_D+I_{Rp}+I \qquad (3.1)$$

We get the following equation for the photovoltaic current:

$$I= I_{ph}-I_{Rp}-I_D \qquad (3.2)$$

$$I = I_{ph} - I_o.\left[exp\left(\frac{V+I.R_S}{V_T}\right)-1\right]-\left[\frac{V+I.R_S}{R_p}\right] \qquad (3.3)$$

Where, I_{ph} is the Insolation current, I is the Cell current, I_0 is the Reverse saturation current, V is the Cell voltage, R_s is the Series resistance, R_p is the Parallel resistance, V_T is the Thermal voltage ($\frac{KT}{q}$), K is the Boltzman constant, T is the Temperature in Kelvin, q is the Charge of an electron.

3.4.1 EFFICIENCY OF PV CELL

The efficiency of a PV cell is defined as the ratio of peak power to input solar power.

$$\eta = \frac{\mathrm{Vmp.Imp}}{\mathrm{I}\left(\frac{\mathrm{KW}}{\mathrm{m}^2}\right).\mathrm{A}(\mathrm{m}^2)} \qquad (3.4)$$

where, V_{mp} is the voltage at peak power, I_{mp} is the current at peak power, I is the solar intensity per square metre, A is the area on which solar radiation fall.

The efficiency will be maximum if we track the maximum power from the PV system at different environmental condition such as solar irradiance and temperature by using different methods for maximum power point tracking.

3.5 MODELLING OF PV ARRAY:

The building block of PV arrays is the solar cell, which is basically a p-n junction that directly converts light energy into electricity: it has a equivalent circuit as shown below in Figure 3.4.

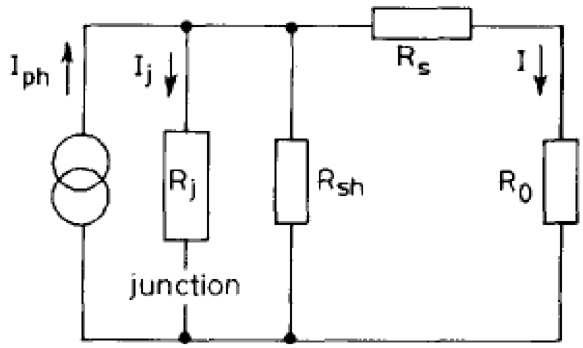

Figure 3.4 Equivalent circuit of a PV cell

The current source I_{ph} represents the cell photo current; Rj is used to represent the non-linear impedence of the p-n junction; R_{sh} and R_s are used to represent the intrinsic series and shunt resistance of the cell respectively. Usually the value of R_{sh} is very large and that of R_s is very small,hence they may be neglected to simplify the analysis. PV cells are grouped in larger units called PV modules which are further interconnected in series-parallel configuration to form PV arrays or PV generators[3].The PV mathematical model used to simplify our PV array is represented by the equation:

$$I=n_pI_{ph}-n_pI_{rs}[\exp(\frac{q}{KTA}*\frac{V}{n_s}) -1] \tag{3.5}$$

where I is the PV array output current; V is the PV array output voltage; n_s is the number of cells in series and n_p is the number of cells in parallel; q is the charge of an electron; k is the Boltzmann's constant; A is the p-n junction ideality factor; T is the cell temperature (K); I_{rs} is the cell reverse saturation current. The factor A in equation (3.5) determines the cell deviation from the ideal p-n junction characteristics; it ranges between 1-5 but for our case A=2.46 [3].

The cell reverse saturation current I_{rs} varies with temperature according to the following equation:

$$I_{rs}=I_{rr}[\frac{T}{T_r}]^3\exp(\frac{qE_G}{KA}[\frac{1}{T_r}-\frac{1}{T}]) \tag{3.6}$$

Where T_r is the cell reference temperature, I_{rr} is the cell reverse saturation temperature at T_r and E_G is the band gap of the semiconductor used in the cell.

The temperature dependence of the energy gap of the semi conductor is given by [20]:
$E_G = E_G(0) - \frac{\alpha T^2}{T+\beta}$ (3.7)

The photo current I_{ph} depends on the solar radiation and cell temperature as follows:

$I_{ph} = [\ I_{scr} + K_i(T - T_r)]\ \frac{S}{100}$ (3.8)

where I_{scr} is the cell short-circuit current at reference temperature and radiation, K_i is the short circuit current temperature coefficient, and S is the solar radiation in mW/cm^2. The PV power can be calculated using equation (3.5) as follows:

$P = IV = n_p I_{ph} V[(\frac{q}{KTA} * \frac{V}{n_s}) - 1]$ (3.9)

3.5.1 PV ARRAY CHARACTERISTIC CURVES

The current to voltage characteristic of a solar array is non-linear, which makes it difficult to determine the MPP. The Figure below gives the characteristic I-V and P-V curve for fixed level of solar irradiation and temperature.

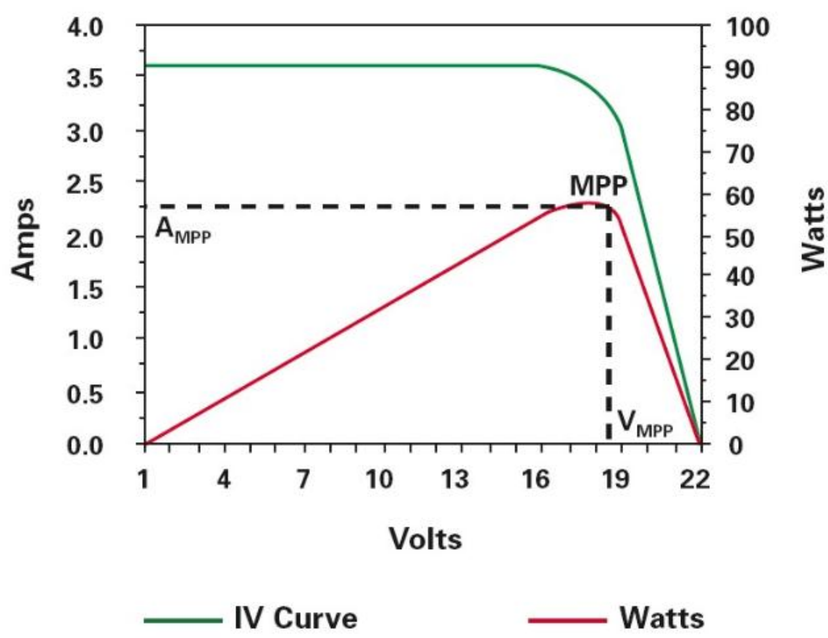

Figure 3.5 I-V and PV curve characteristics [19].

The IV and PV curves for various irradiance but a fixed temperature (25^0C) is shown below in Figure (3.6)& (3.7).The characteristic I-V curve tells that there are two regions in the curve: one is the current source region and another is the voltage source region. In the voltage source region (in the right side of the curve), the internal impedance is low and in the current source region (in the left side of the curve),the impedance is high. Irradiance temperature plays an important role in predicting the I-V characteristic, and effects of both factors have to be considered while designing the PV system. Whereas the irradiance affects the output, temperature mainly affects the terminal voltage. The figures (3.8), (3.9) gives the simulated I-V and P-V characteristic for various temperatures at a fixed irradiance at 1000 W/m^2 [4].

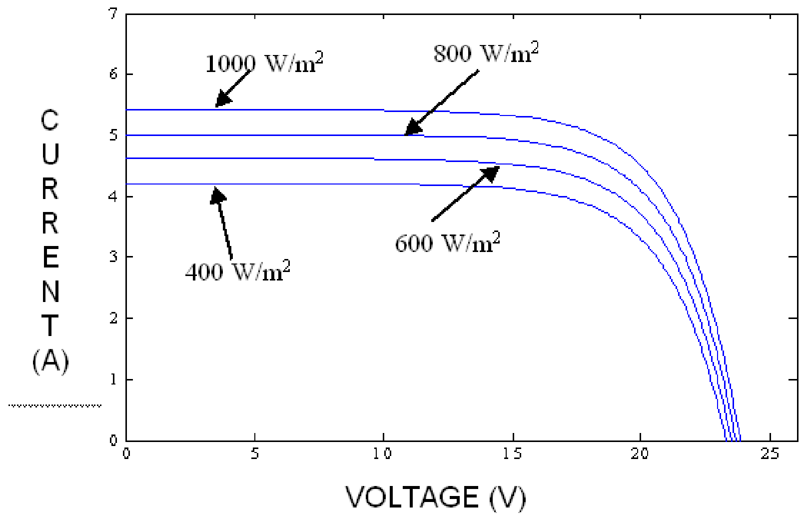

Figure 3.6 I-V characteristic of a solar array for a fixed temperature but varying irradiance

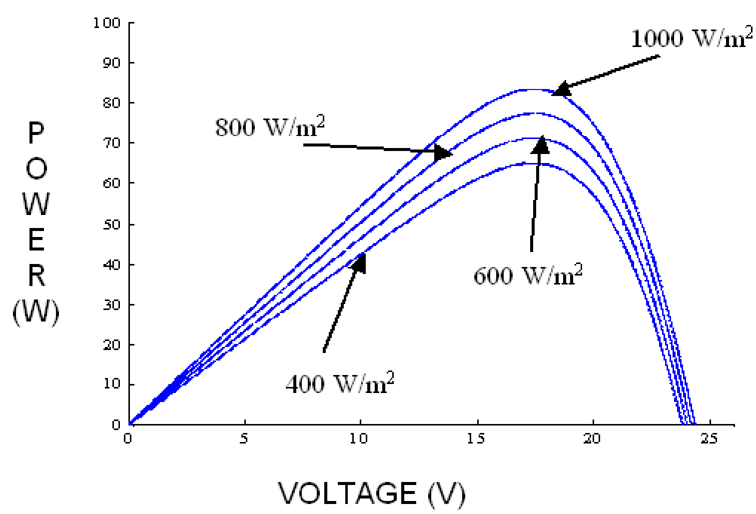

Figure 3.7 P-V characteristic of a solar array for a fixed temperature but varying irradiance

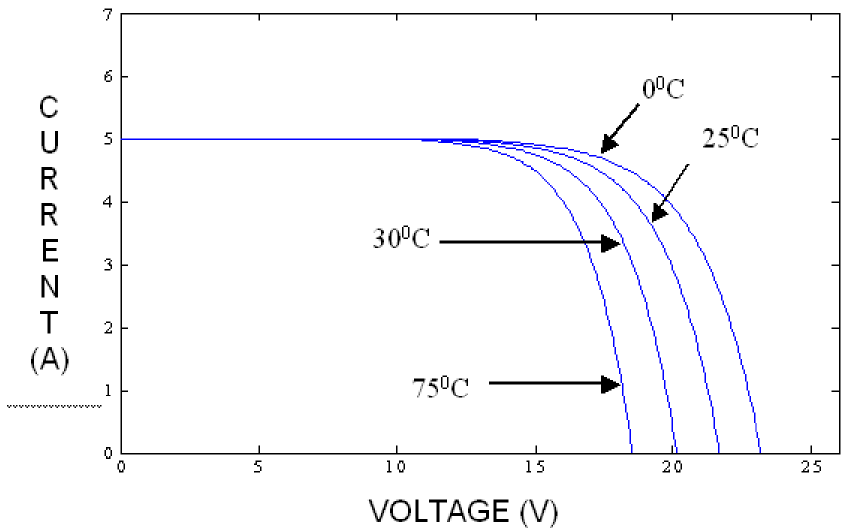

Figure 3.8 I-V Characteristic of a PV array under a fixed irradiance but varying temperatures

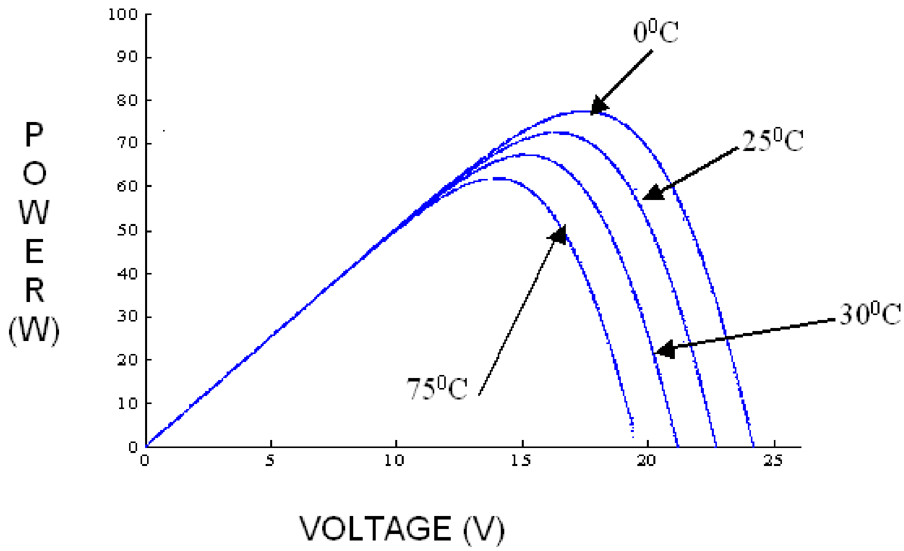

Figure 3.9 P-V Characteristic of a PV array under a fixed irradiance but varying temperatures.

From the I-V, we observe that the short circuit current increases with increase in irradiance at a fixed temperature. Moreover, from the I-V and P-V curves at a fixed irradiance, it is observed that the open circuit voltage decreases with increase in temperature.

3.5.2 MATLAB CODE FOR PV ARRAY

```
T=28+273;
Tr1=40;  %   Reference temperature in degree fahrenheit
Tr=((Tr1-32)*5/9)+273;  %   Reference temperature in kelvin
S=[100 80 60 40 20];    %   Solar radiation in mW/sq.cm
%S=70;
ki=0.00023;  %   in A/K
Iscr=3.75; %    SC Current at ref. temp. in A
Irr=0.000021;   % in A
k=1.38065*10^(-23);  %   Boltzmann constant
q=1.6022*10^(-19);  %   charge of an electron
A=2.15;
Eg(0)=1.166;
alpha=0.473;
beta=636;
Eg=Eg0-(alpha*T*T)/(T+beta)*q;           %       band   gap   energy   of
semiconductor used

cell in joules
Np=4;
Ns=60;
V0=[0:1:300];
for i=1:5
Iph=(Iscr+ki*(T-Tr))*((S(i))/100);

Irs=Irr*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));

I0=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V0./Ns)-1);
P0 = V0.*I0;
figure(1)
plot(V0,I0);
axis([0 50 0 20]);
xlabel('Voltage in volt');
ylabel('Current in amp');
hold on;
```

```
figure(2)
plot(V0,P0);
axis([0 50 0 400]);
xlabel('Voltage in volt');
ylabel('Power in watt');
hold on;
figure(3)
plot(I0,P0);
axis([0 20 0 400]);
xlabel('Current in amp');
ylabel('Power in watt');
hold on;
end
```

Chapter **4**

CONVERTERS

4.1 DC-DC CONVERTERS

DC-DC converters can be used as switching mode regulators to convert an unregulated dc voltage to a regulated dc output voltage. The regulation is normally achieved by PWM at a fixed frequency and the switching device is generally BJT, MOSFET or IGBT. The minimum oscillator frequency should be about 100 times longer than the transistor switching time to maximize efficiency. This limitation is due to the switching loss in the transistor. The transistor switching loss increases with the switching frequency and thereby, the efficiency decreases. The core loss of the inductors limits the high frequency operation. Control voltage V_c is obtained by comparing the output voltage with its desired value. Then the output voltage can be compared with its desired value to obtain the contol voltage V_{cr}. The PWM control signal for the dc converter is generated by comparing V_{cr} with a sawtooth voltage V_r.[8]. There are four topologies for the switching regulators: buck converter, boost converter, buck-boost converter, cứk converter. However my project work deals with the boost regulator and further discussions will be concentrated towards this one.

4.2 BOOST CONVERTER AND ITS OPERATION

The figure (4.1) below shows a step up or PWM boost converter. It consists of a dc input voltage source V_g, boost inductor L, controlled switch S, diode D, filter capacitor C, and the load resistance R. When the switch S is in the on state, the current in the boost inductor increases linearly and the diode D is off at that time. When the switch S is turned off, the energy stored in the inductor is released through the diode to the output RC circuit[8].

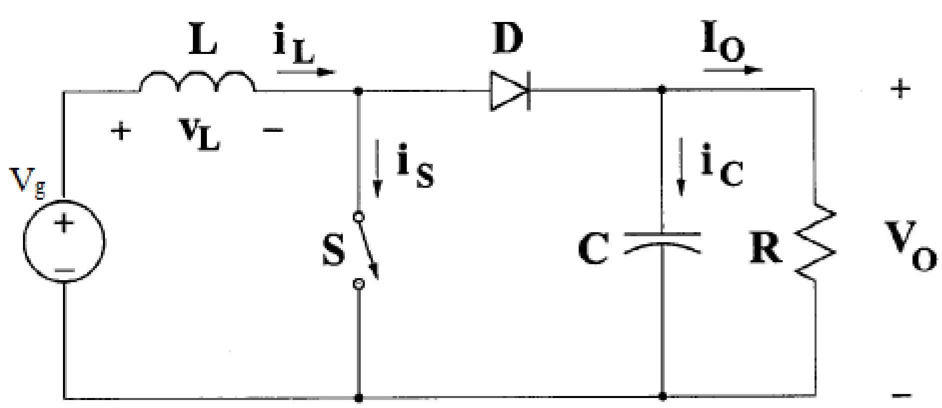

Figure 4.1 Circuit diagram of boost converter

4.2.1 STEADY STATE ANALYSIS OF THE BOOST CONVERTER

(a) OFF STATE:

In the OFF state, the circuit becomes as shown in the Figure (4.2) below [9].

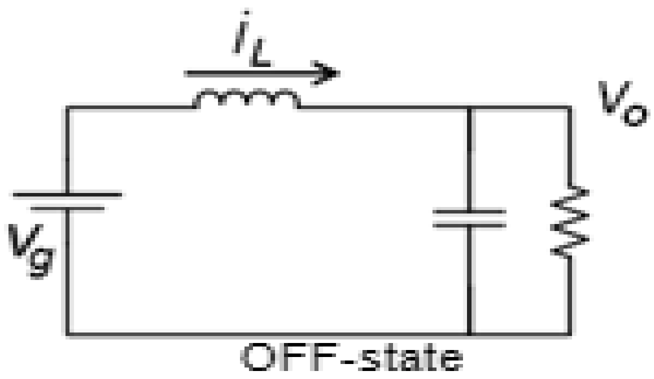

Figure 4.2 The OFF state diagram of the boost converter

When the switch is off, the sum total of inductor voltage and input voltage appear as the load voltage.

(b) ON STATE:

In the ON state, the circuit diagram is as shown below in Figure (4.3):

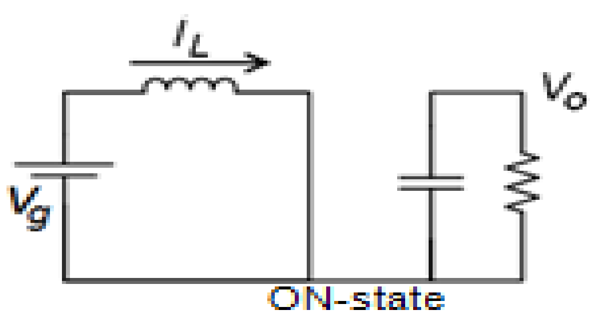

Figure 4.3 The ON state diagram of the boost converter

When the switch is ON, the inductor is charged from the input voltage source V_g and the capacitor discharges across the load. The duty cycle, D= $\frac{T_{on}}{T}$ where T=$\frac{1}{f}$

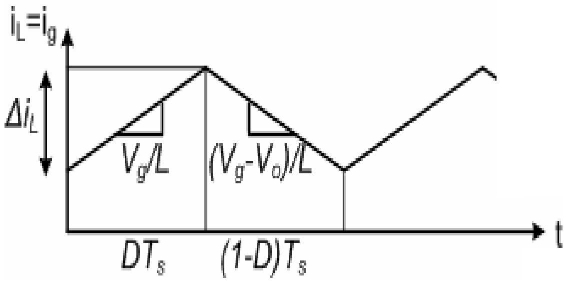

Figure 4.4 Inductor current waveform

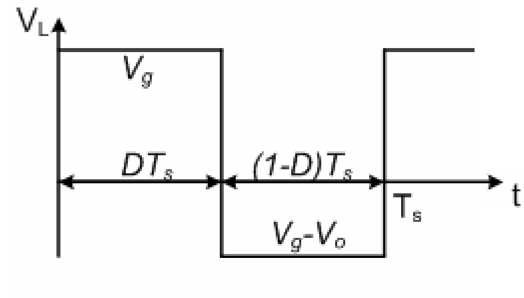

Figure 4.5 Inductor voltage waveform

From the inductor voltage balance equation, we have:-

$$V_g(DT_s) + (V_s-V_o)(1-D)T_s=0$$

$$\Rightarrow V_g(DT_s)-V_g(DT_s)-V_gT_s+V_oDT_s-V_oT_s=0$$

$$\Rightarrow V_o=V_g/(1-D)$$

$\Rightarrow$Conversion ratio, $M=V_o/V_g=1/(1-D)$ (4.1)

From inductor current ripple analysis, change in inductor current,

$$\Delta I_l=(I_{max}-I_{min})$$

$$\Rightarrow \Delta I_L=(V_g/L)*(DT_s)$$

$$\Rightarrow \Delta I_L = (V_gD)/(f_sL)$$

$$\Rightarrow L=V_gD/f_s(\Delta I_L) \tag{4.2}$$

The boost converter operates in CCM (continuous conducting mode) for $L> L_b$ where

$$L_b= \frac{(1-D)2DR}{2f} \tag{4.3}$$

The current supplied to the output RC circuit is discontinuous. Thus a large filter capacitor is used to limit the output voltage ripple. The filter capacitor must provide the output dc current to the load when the diode D is off.

The minimum value of the filter capacitance that results in the voltage ripple V_r[8] is given by:

$$C_{min} = \frac{DV_0}{V_0 Rf} \tag{4.4}$$

4.2.2 DESIGN OF THE BOOST CONVERTER

(1) CURRENT RIPPLE FACTOR (CRF):

According to IEC harmonics standard, CRP should be bounded within 30%.

i.e $\frac{\Delta I_1}{I_1} = 30\%$ (4.5)

(2) VOLTAGE RIPPLE FACTOR (VRF):

i.e $\frac{\Delta V_0}{V_0} = 5\%$ (4.6)

(3) SWITCHING FREQUENCY (f_s):

F_s= 100 KHz (4.7)

GIVEN DATA:

- Input voltage, V_g=25V
- Output voltage, V_o=300V
- Output load current, I_o=1A

Step 1 : Calculation of Duty cycle (D):

$$\frac{V_0}{V_g} = \frac{1}{1-D}$$

$$\Rightarrow \frac{1}{1-D} = \frac{300}{25}$$

$$\Rightarrow D = 11/12 = .9166 \qquad (4.8)$$

Step 2: Calculation of Ripple Current(ΔI_L):

I_L= 1 A

$$\Rightarrow \Delta I_L = (0.3 * 1)\text{A} = 0.3\text{ A} \qquad (4.9)$$

Step 3: Calculation of Inductor value (L):

$$L = \left(\frac{Vg * D}{f * \Delta I_L}\right) = (25*.9166)/(0.3*10\text{^}5) = 7.63 * 10\text{^} -4\text{ H}. \qquad (4.10)$$

Step 4: Calculation of capacitor value(C) :

We have, $\frac{\Delta V_0}{V_0} = \frac{DTs}{R_0 C}$ (4.11)

$R_0 = \frac{V_0}{I_0} = 300/1 = 300\Omega$. (4.12)

$C = D/f * R_0 * (\Delta V_0/V) = (.9166)/(10\text{^}5)*(300)*(.05) = .611\ \mu F$. (4.13)

The transfer function of the boost converter[12] used for the modeling is given by:

$$G(s) = \frac{V_O}{1-D} * \frac{1-\frac{Ls}{(1-D)^2 * R}}{\frac{LCs^2}{(1-D)^2}+\frac{Ls}{(1-D)^2 R}+1} \qquad (4.14)$$

Putting the values of R, L, C, D, V_g in the above equation, the transfer equation that results is given by:

$$G(s) = \frac{25*(300-(100.716*10\text{^}-3))}{((.139*10\text{^}-6)*S\text{^}2)+0.763*(10\text{^}-3)*S+2.08} \qquad (4.15)$$

By trial and error, we get the value of K_P which gives desired results as 6.03.

4.3 INTERFACING OF THE PV ARRAY WITH BOOST CONVERTER

The PV array has been interfaced with the boost converter using a controlled voltage source as shown in the circuit diagram below:

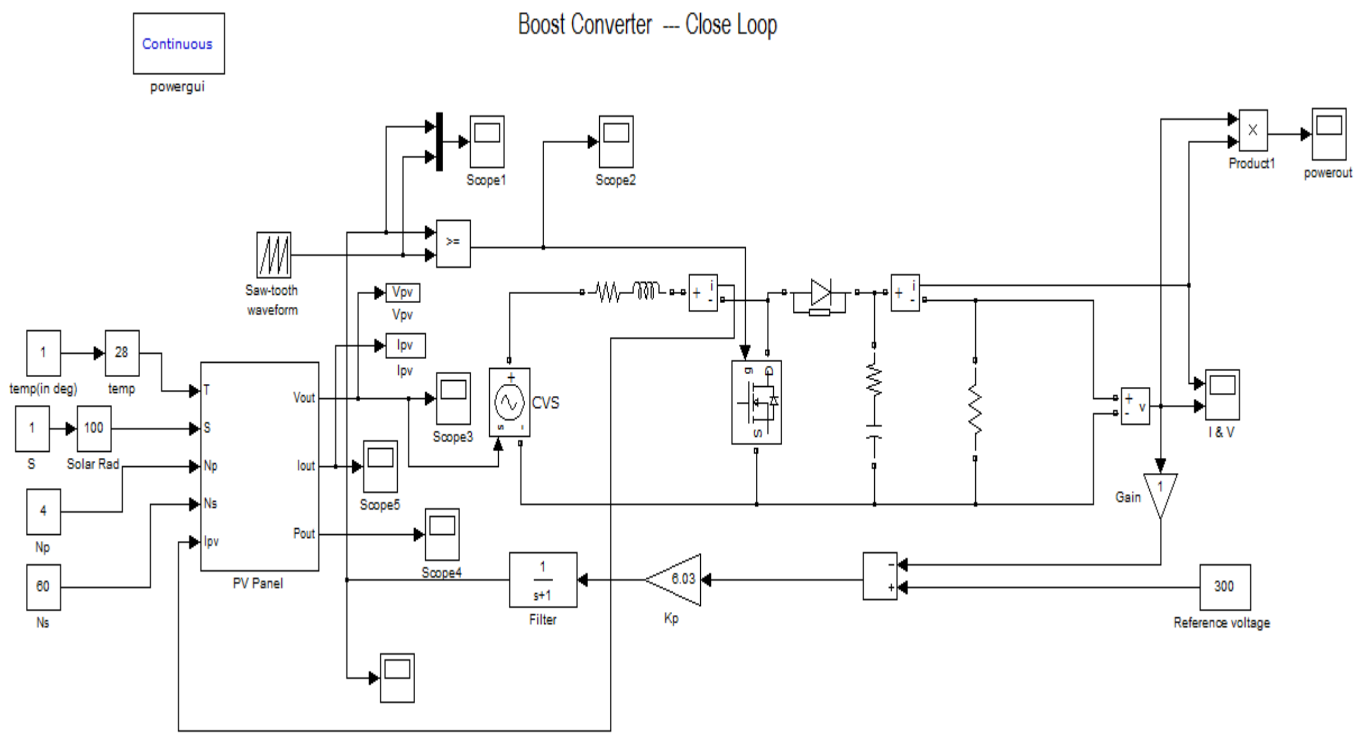

Figure 4.6 The complete simulink circuit model showing the coupling of PV array with the boost converter

The PV array has been designed taken into consideration its dependence upon the irradiance, temperature, number of PV cells connected in series and parallel as explained in chapter 2[4]. The detailed internal circuit of the PV array showing the design is given below:

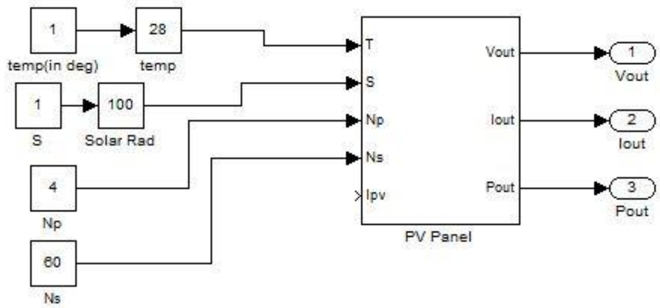

Figure 4.7 PV panel block diagram

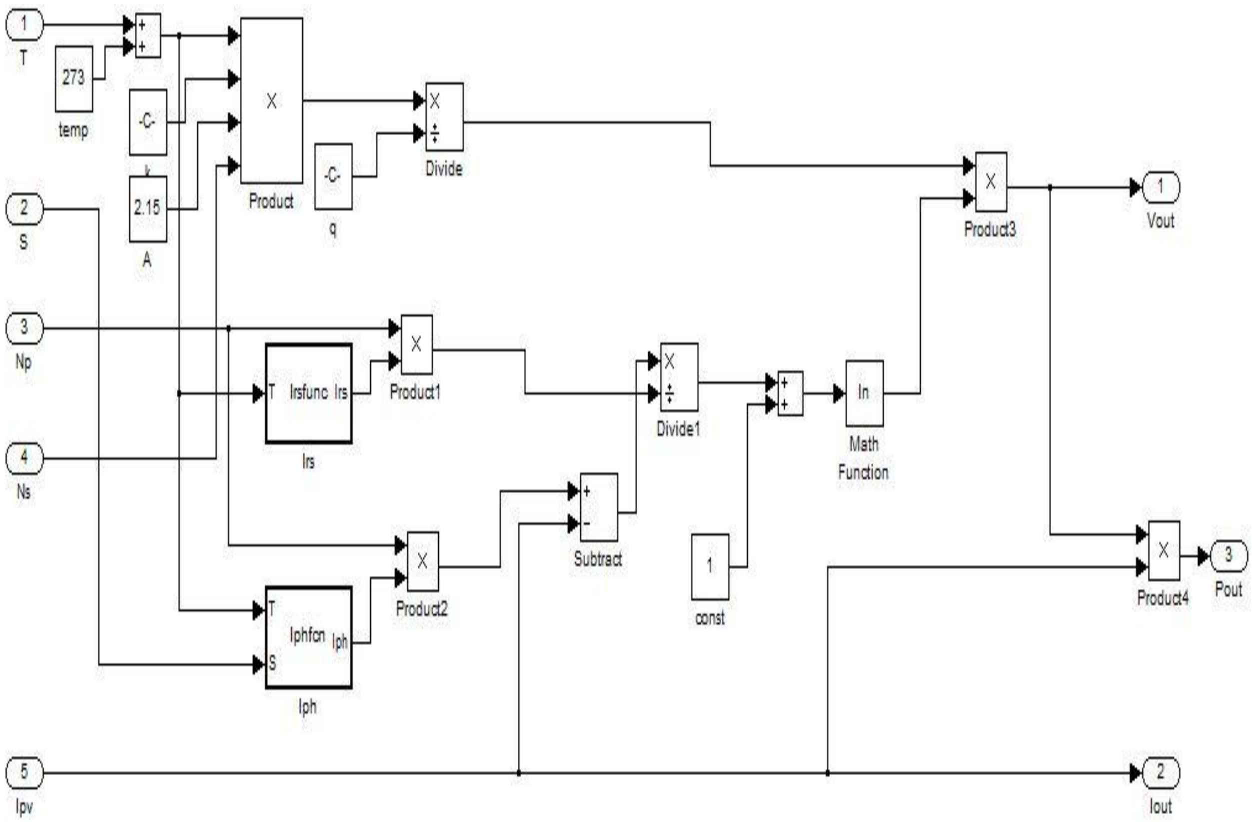

Figure 4.8 Detailed internal circuit diagram of PV array in simulink

The M-file for I_{rs} function has been developed using the equation (3.6) and that for the I_{ph} function using equation (3.8). The PV array has been modeled using the equations (3.1) – (3.9). The interfacing of the PV array with the boost converter has been achieved using a voltage controlled source. The inductor current which is same as the load current of the PV system is used as feedback for designing the PV array.

Chapter **5**

RESULTS AND DISCUSSIONS

5.1 PARAMETERS USED IN THE MATLAB CODE

The values of the parameters used in developing the MATLAB code for the Photovoltaic array have been tabled below[1], [20]:

Table 1: Parameters value used in MATLAB code

PARAMETERS	VALUES
N_p	4
N_s	60
I_{scr}	3.75 A
T_{r1}	40 ^{0}C
K_i	0.00023 A/K
I_{rr}	0.000021 A
K	1.38065 * 10^{-23} J/^{0}K
q	1.6022* 10^{-19} C
A	2.15
E_g0	1.66 eV
α	4.73* 10^-4 eV/K
β	636 K

5.2 OUTPUT WAVEFORMS OF THE PV ARRAY

The waveforms obtained by varying the solar insolation and temperatures which are fed into the PV array model have been plotted as shown below:

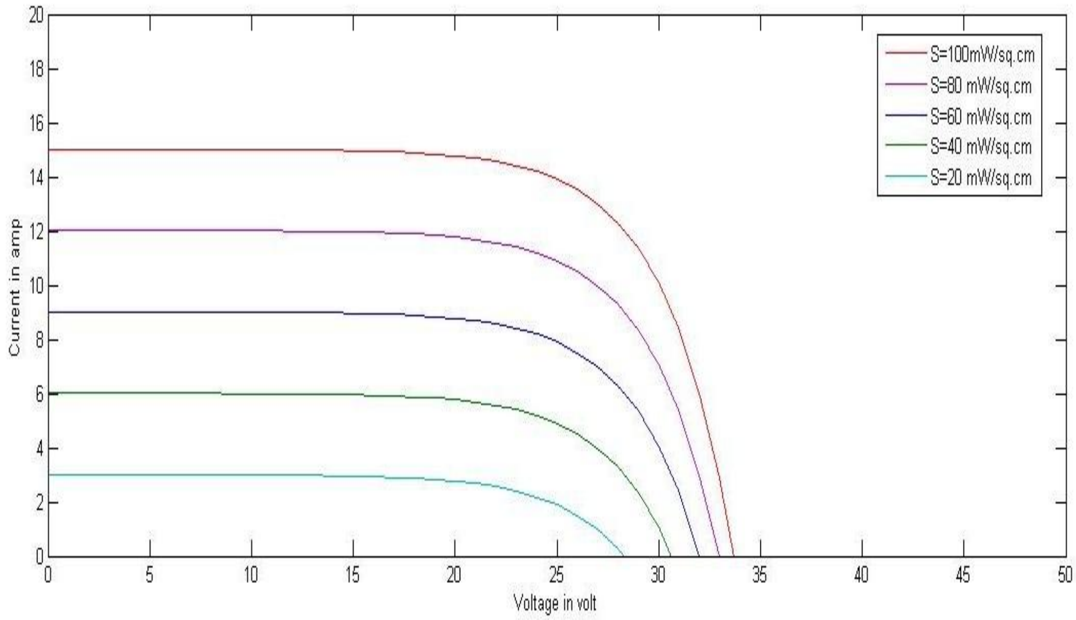

Figure 5.1 I-V curves obtained at 28^0C for various irradiance levels

From Figure(5.1), we observed that by increasing the solar radiation at constant temperature the voltage and current output from PV array also increases.Hence at higher insolation we can get our required level voltage.

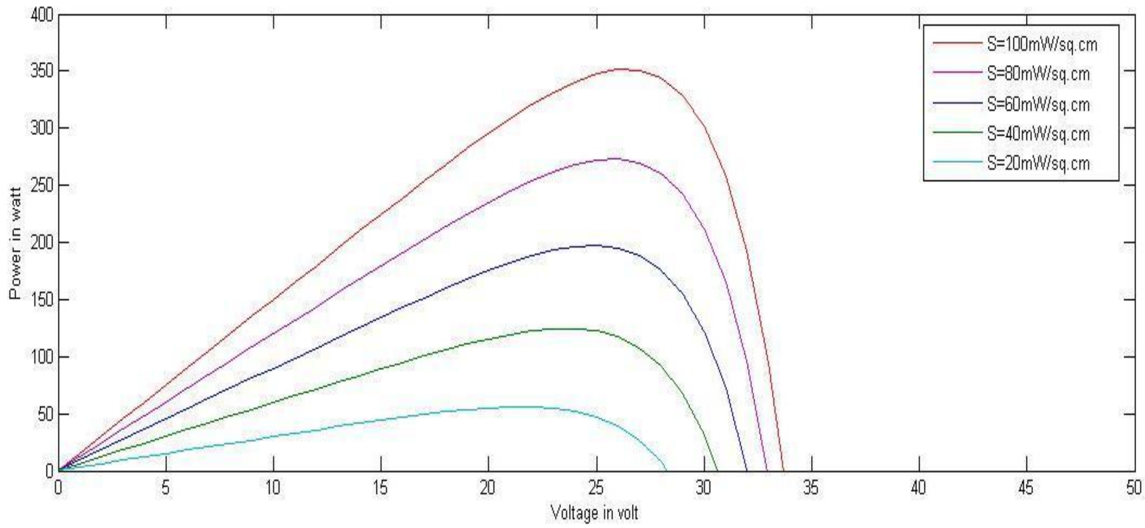

Figure 5.2 P-V curves obtained at 28^0C for various irradiance levels

From Figure (5.2), we observed that by increasing the solar insolation level, the power output from PV array increases.

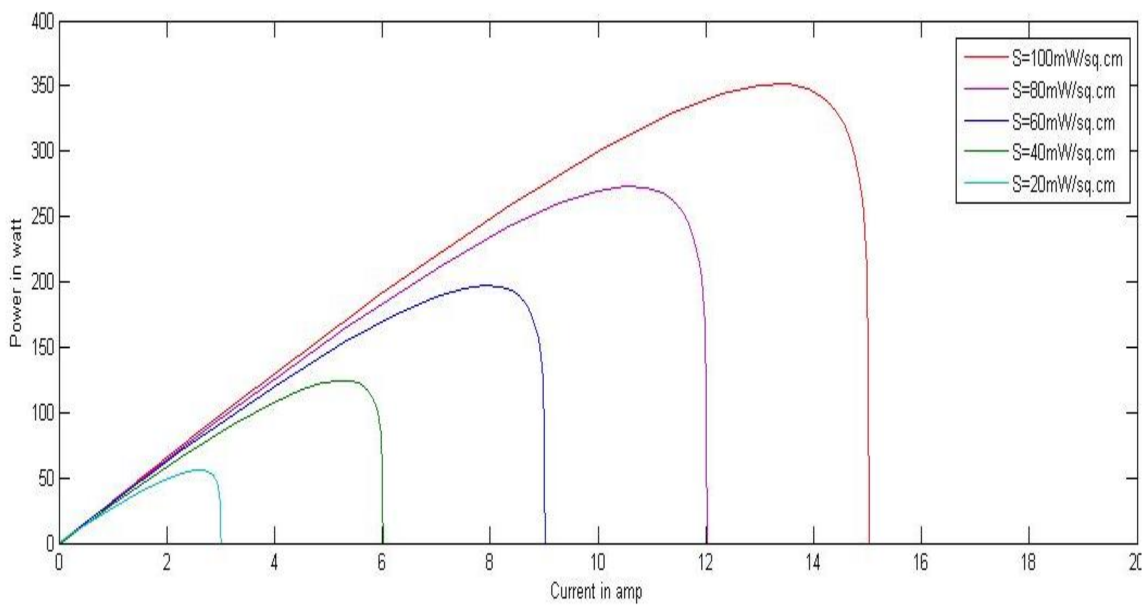

Figure 5.3 P-I curves obtained at 28^0C for various irradiance levels

From figure (5.3), we observed that by increasing the solar radiation level, the current and power output from PV array increases.

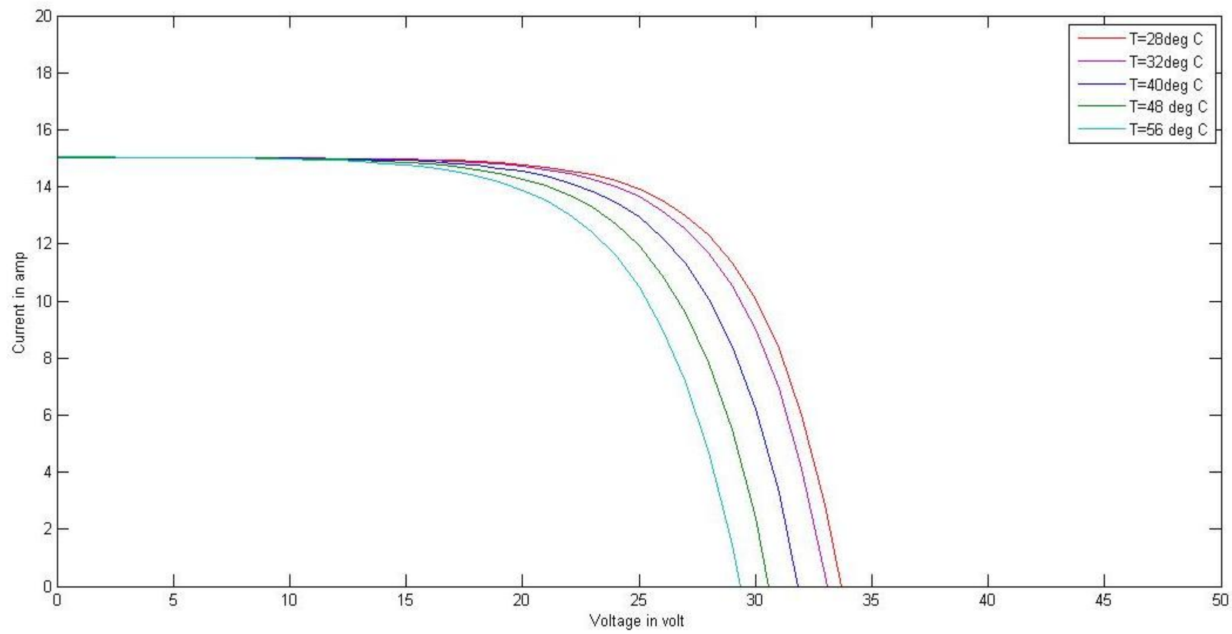

Figure 5.4 I-V curves obtained at an irradiance of 100 mW /cm^2 for various temperatures.

From figure(5.4), we observed that by increasing the temperature level at constant irradiance, the voltage output from PV array decreases but current output increases slightly with respect to voltage and, hence the power output from PV array decreases.

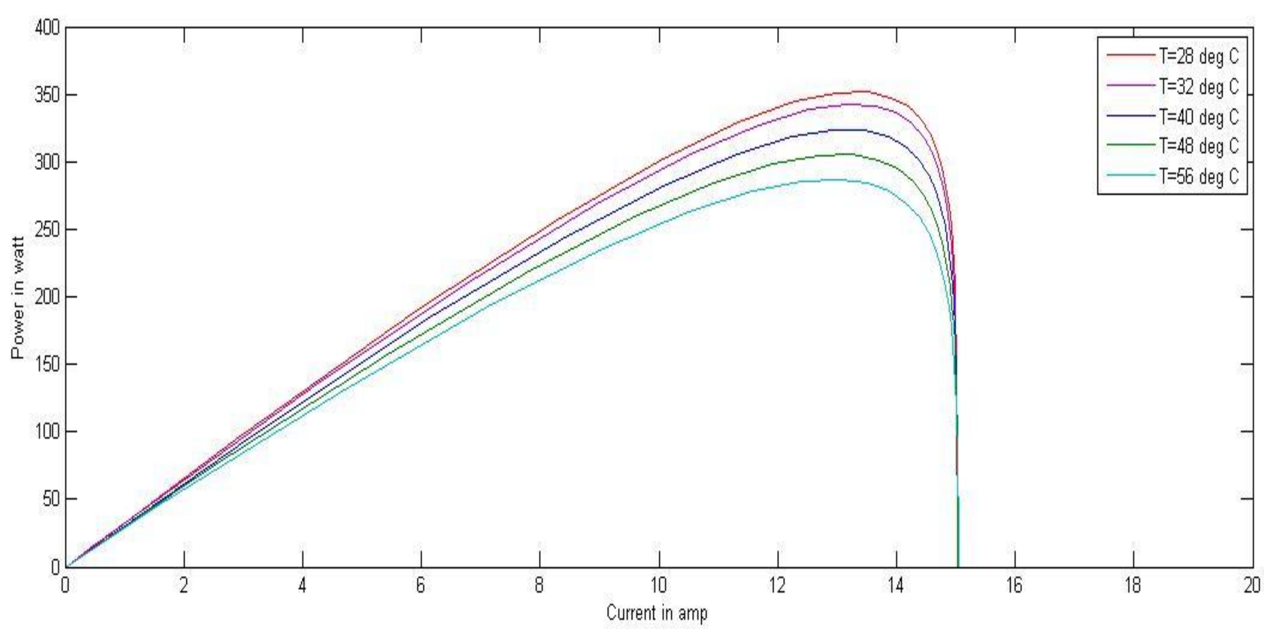

Figure 5.5 P-I curves obtained at an irradiance of 100 mW/cm^2 for various temperatures.

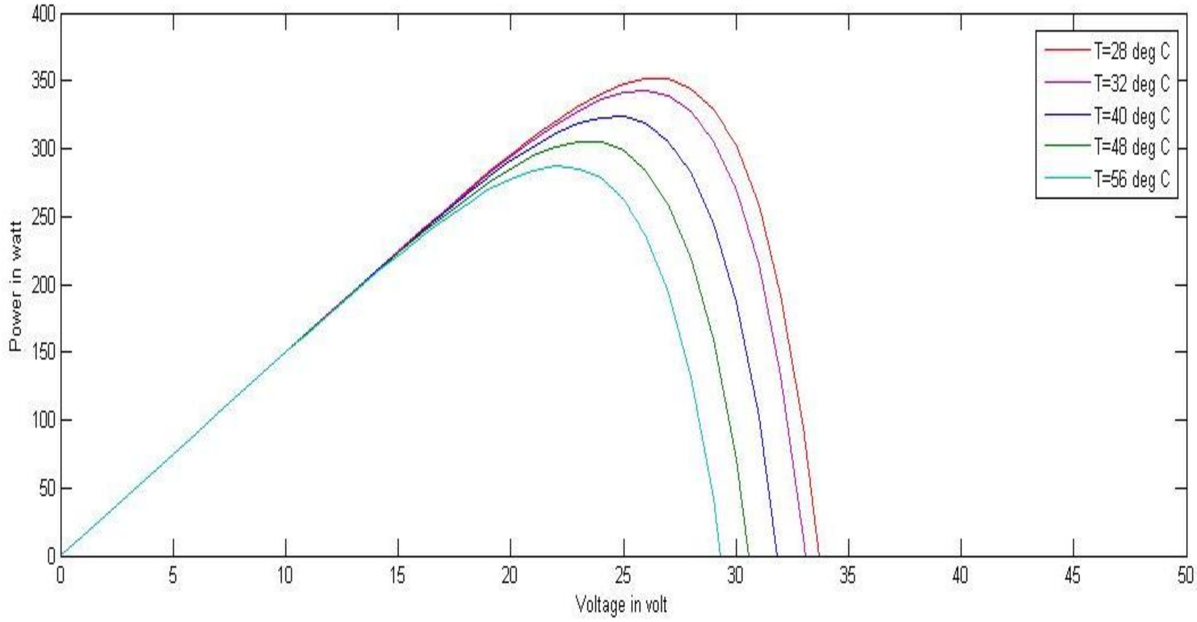

Figure 5.6 P-V curves obtained at an irradiance of 100 mW/cm^2 various temperatures.

5.3 SIMULINK MODEL

The Figure (5.7) below shows the block diagram of the complete circuit. This includes the PV module, boost converter and control circuit. The modeling and simulation of the whole system has been done in MATLAB-SIMULINK environment.

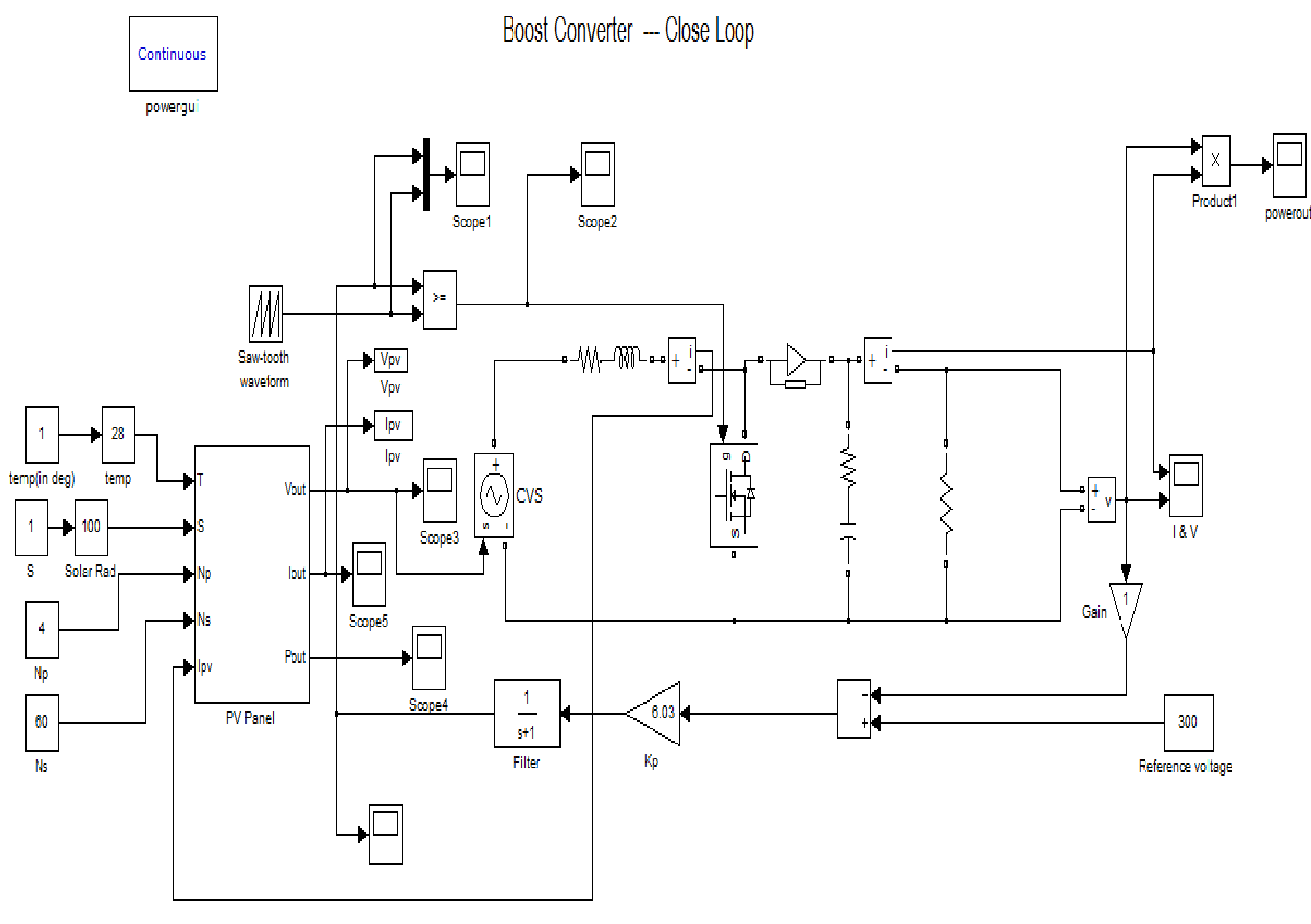

Figure 5.7 The complete simulation model of the PV energy conversion system.

5.4 GENERATION OF THE PWM SIGNAL

The simulink model for the generation of the PWM signal is shown below:

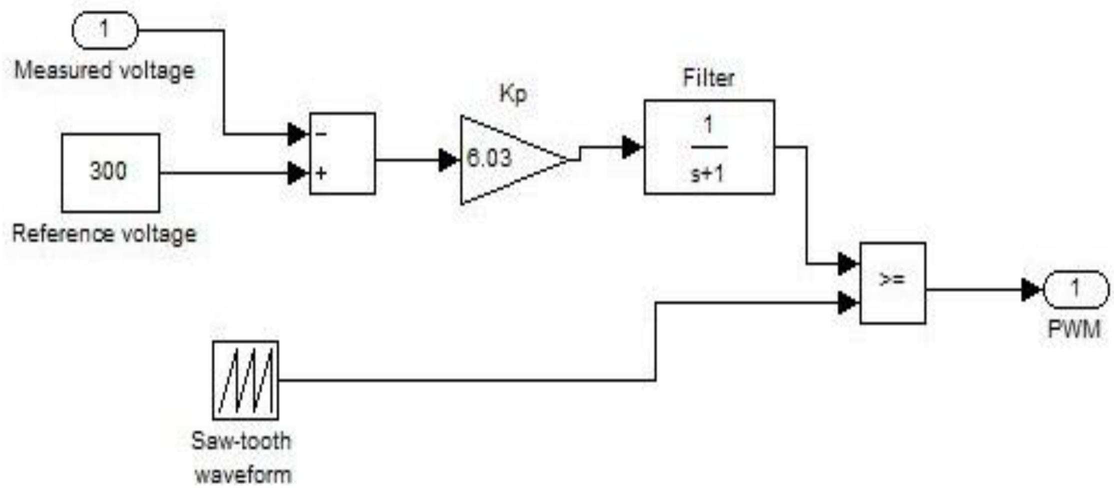

Figure 5.8 Circuit diagram for PWM signal generation

The output of the filter which is the control signal is compared with the saw-tooth waveform having a peak voltage of 25V to generate the PWM signal which is fed as gate signal to the MOSFET. The simulation diagram showing the comparison of the saw-tooth waveform with the control signal is shown below:

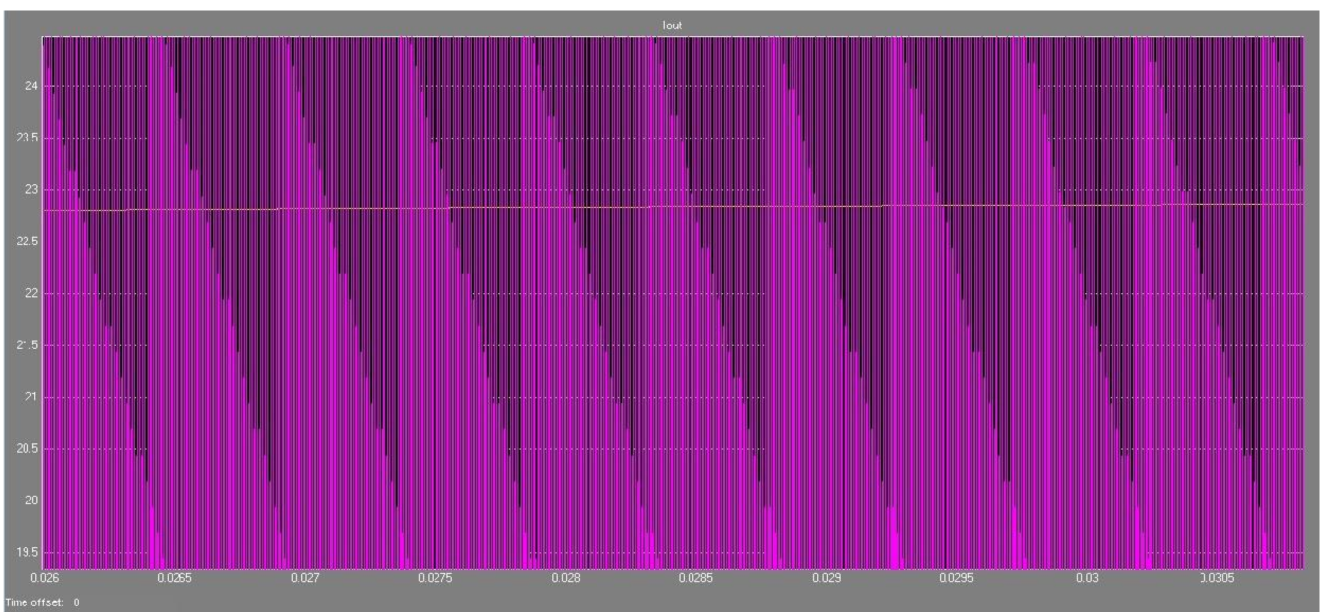

Figure 5.9 Simulation diagram showing the generation of the PWM signal

The required PWM signal used as the gate pulse for the MOSFET is shown below in the figure:

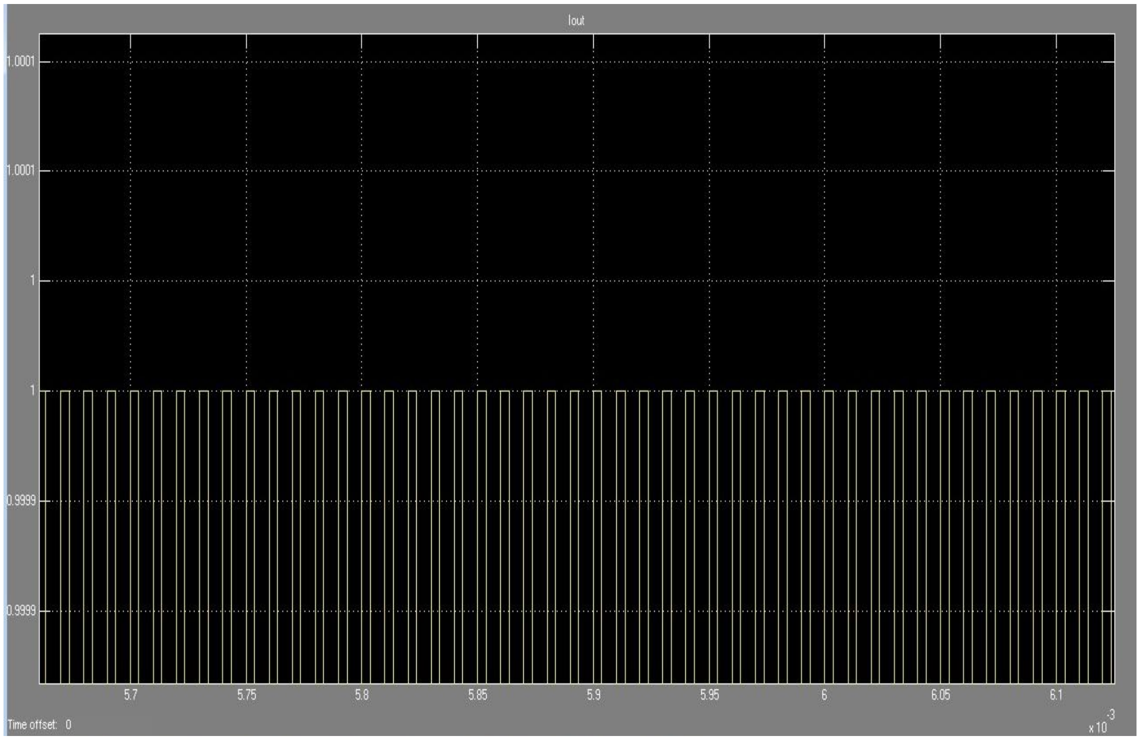

Figure 5.10 PWM signal generated

5.5 SIMULATION RESULTS

The output I_{out} and V_{out} curves obtained across the load resistance of the boost converter of the simulink model as shown in above Figure(5.11) is drawn below.

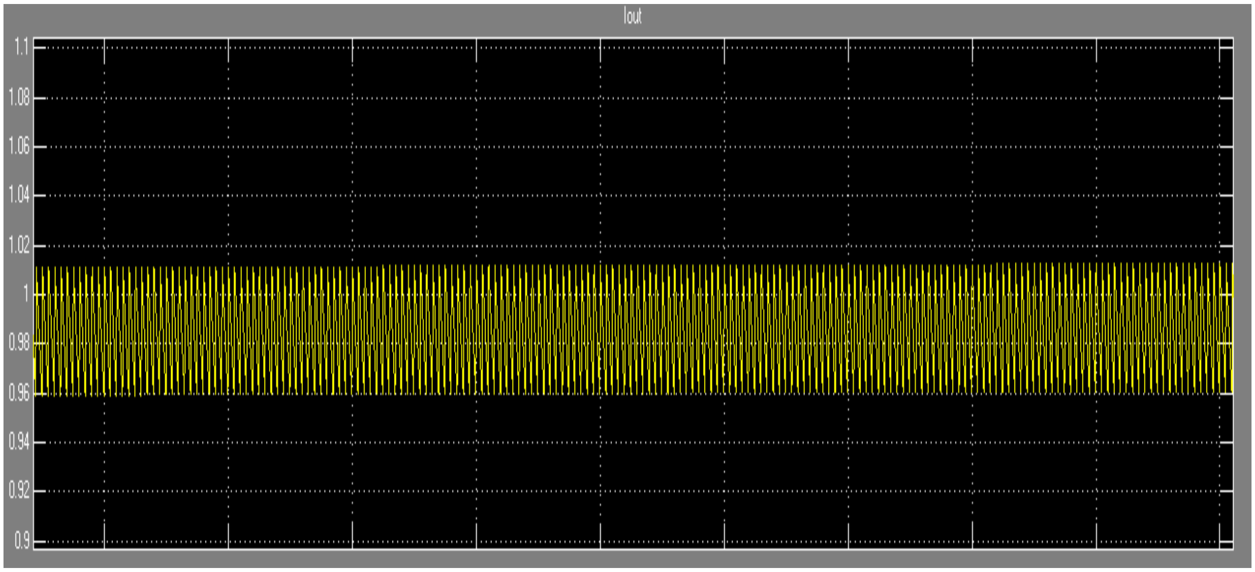

Figure 5.11 The current output of the system

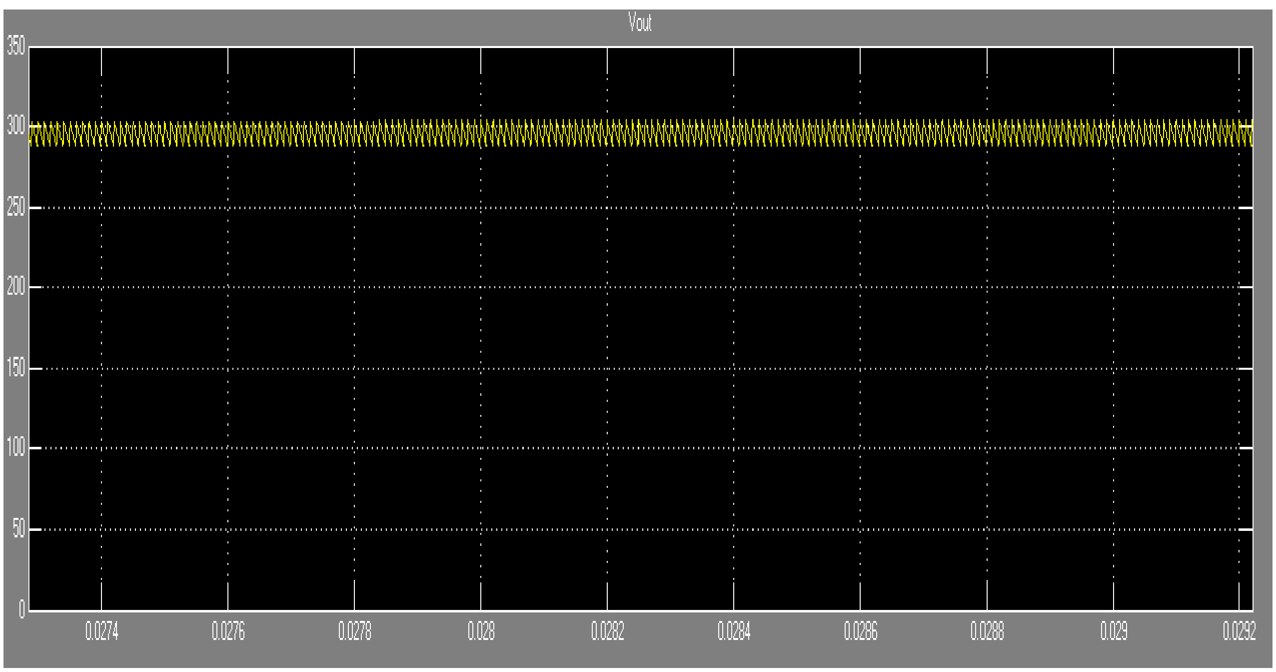

Figure 5.12 The voltage output across the load resistance of the boost converter

5.6 RESULTS CONFIRMING PROPER COUPLING OF PV ARRAY WITH BOOST CONVERTER

The load resistance of the close loop boost converter is varied and the values of the input voltage and current fed to the converter are noted for various levels of insolation. The values of the current and voltage obtained are plotted in the open circuit I-V curve of the PV array. The values obtained follow the curve closely thereby fulfilling our requirements. The tabulation and the curves which verify our successful simulation model is given below:

Table 2: Value of input voltage and current for variation in load resistance for an irradiance level (100 mW/m^2)

INSOLATION(mW/m^2)	LOAD RESISTANCE(Ω)	INPUT VOLTAGE(Volt)	INPUT CURRENT(Amp)
100	300	28.92	11.42
100	285	27.2	12.86
100	450	31.62	6.898

Table 3: Value of input voltage and current for variation in load resistance for an irradiance level (80 mW/m^2)

INSOLATION(mW/m^2)	LOAD RESISTANCE(Ω)	INPUT VOLTAGE(Volt)	INPUT CURRENT(Amp)
80	400	28.75	8.58
80	450	29.75	7.382
80	680	31.26	4.726

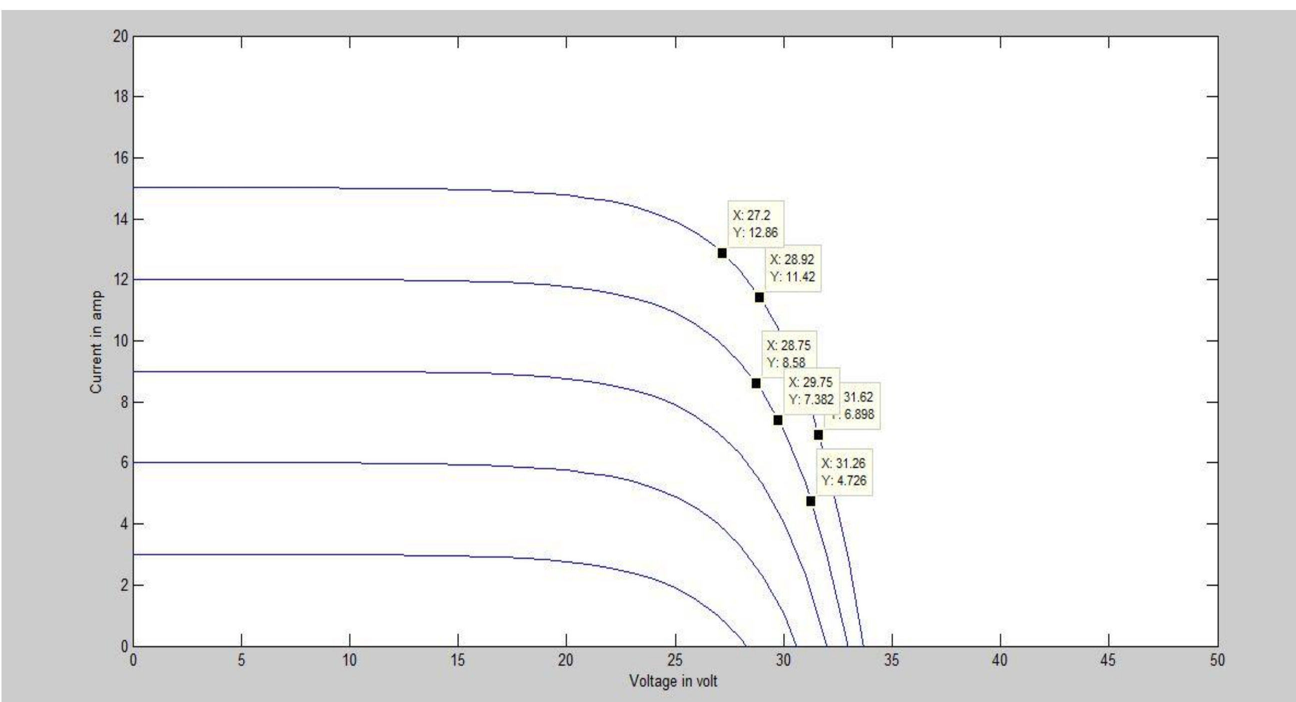

Figure 5.13 Interfacing of PV array simulation result with open loop I-V characteristic

Chapter **6**

CONCLUSIONS

The open circuit P-V, P-I, I-V curves we obtained from the simulation of the PV array designed in MATLAB environment explains in detail its dependence on the irradiation levels and temperatures. The entire energy conversion system has been designed in MATLB-SIMULINK environment. The various values of the voltage and current obtained have been plotted in the open circuit I-V curves of the PV array at insolation levels of 100 mW/cm^2 and 80 mW/cm^2. The voltage and current values lie on the curve showing that the coupling of the PV array with the boost converter is proper. However the performance of the photovoltaic device depends on the spectral distribution of the solar radiation.

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